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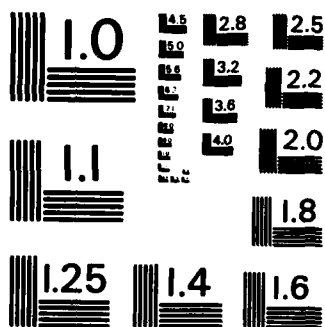
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IRREGULARITY DECAY IN AN
ISOLATED PLASMA BUBBLE

R.C. Livingston
J.F. Vickrey

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Scientific Report No. 1

31 May 1984

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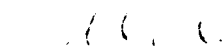
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I INTRODUCTION

Irregularity generation in the nighttime equatorial F region is dominated by the large-scale electron density structures that have come to be known as plasma bubbles. These depleted regions and the irregularities that they produce as they develop, are clearly associated with radar backscatter, ionogram spread F, airglow depletions and radio-wave scintillation [Ossakow, 1979, and references cited therein].* Typically, the experimental effort has been directed toward understanding the growth and full-development phases of plasma bubbles in the early evening local-time sector. In this paper, we describe measurements of a much weaker, decay phase bubble. By making repeated scans through that bubble, detailed changes in its irregularity content have been measured.

The observations were made using the Air Force Geophysics Laboratory's (AFGL) Airborne Ionospheric Observatory. Previous measurements using the aircraft have established the bottomside airglow, spread-F and intensity scintillation signatures of equatorial plasma bubbles [e.g., Weber et al., 1980]. In early 1979, the scintillation measurement capability of the aircraft was expanded to record complex signal measurements from CW satellite sources using a technique outlined in Livingston [1983]. The phase of a transionospherically propagated signal is not strongly affected by diffraction at the frequencies and perturbation levels of interest here [Rino, 1979], and its power spectrum provides an almost direct mapping of the in situ irregularity continuum. The inherent sensitivity of the phase measurements also makes it possible to observe subtle changes in that continuum over a large range of spatial scales. This time/wavelength dependence of spectral energy is an essential element in the definition of irregularity decay.

*The references are listed at the end of this report.

II EXPERIMENT BACKGROUND

The observations included in this paper were made during a flight from Ascension Island on 27 and 28 March 1979; the objective of that flight was to locate an isolated, eastward-drifting plasma depletion, and to make repeated scintillation measurements through the disturbance as it decayed. A route was selected far enough south of the magnetic equator to ensure high enough background airglow intensities at 6300 Å to contrast with the plasma bubbles and associated airglow depletions. Early in the flight, one moderate airglow depletion was observed, but the structure had decayed before any propagation raypaths intersected the disturbance. A second depletion was encountered shortly thereafter, and at local times between 2300 to 0130 hours, a series of east-west legs were flown to make repeated scintillation and optical measurements of the bubble as it decayed.

Figure 1 is a map of the F-region (350-km) penetration point scanned by the aircraft during the multiple east-west flight legs. The successive tracks are nearly parallel, and each is at a constant dip latitude near 13° . The radio-scintillation source used throughout the scintillation measurements was a 249-MHz signal from a geostationary satellite located due west of the aircraft at an elevation of 73° . The aircraft speed was nearly constant in both eastward and westward directions producing a cross-field penetration velocity component of slightly greater than 200 m/s at F-region altitudes.

Figure 2 shows the all-sky 6300-Å airglow images for three times during the flight. The dots indicate the propagation-path intersection at the assumed airglow emission height of 250 km, where the all-sky lens images a circle of 600-km radius in the ionosphere. The airglow depletions visible in Figure 2, although structured, are relatively weak compared to others measured near Ascension Island in 1978 [Weber et al., 1980]. They do, however, verify that it is the same structure that is being intercepted on consecutive aircraft passes.

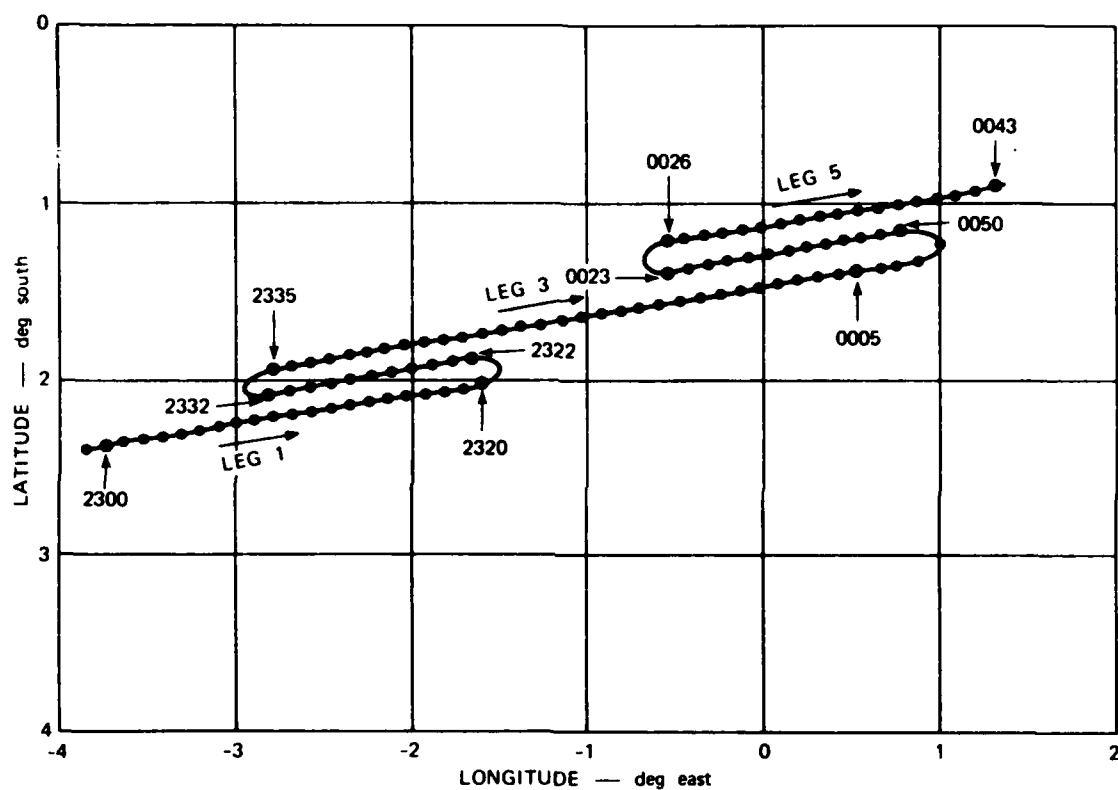


FIGURE 1 MAP OF THE 350-km ALTITUDE IONOSPHERIC PENETRATION POINT FOR CONSECUTIVE EAST-WEST FLIGHT LEGS

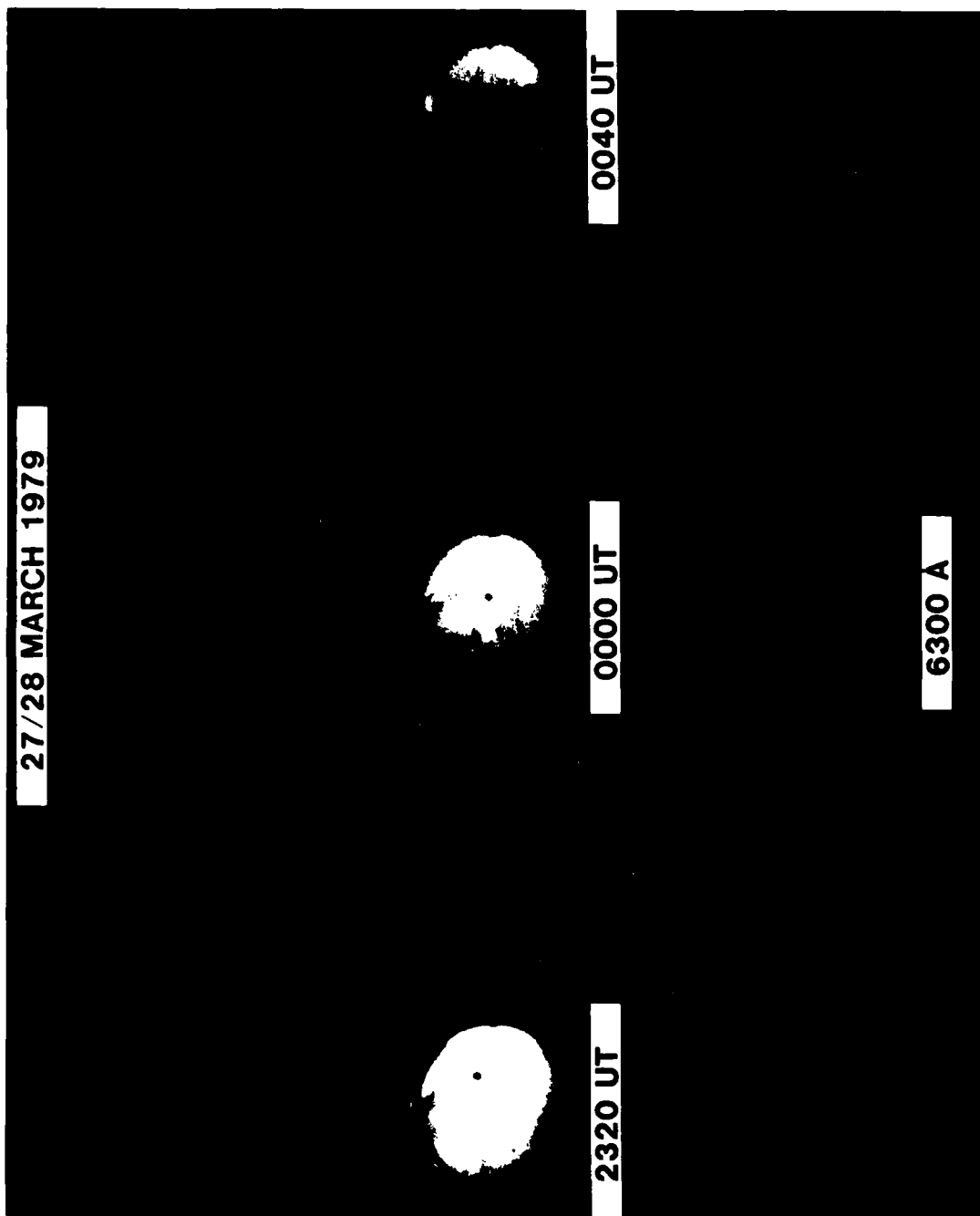


FIGURE 2 6300-Å AIRGLOW IMAGES OF THE BUBBLE, WITH THE IONOSPHERIC PENETRATION POINT INDICATED

III STRUCTURE OF TOTAL ELECTRON CONTENT AND INTENSITY SCINTILLATION

Figure 3(a) shows the signal intensity and large-scale dispersive phase variation, flying eastward for Leg 1, the first scan through the bubble. The onset of intensity scintillation, which is caused by irregularities of ~ 200 -m cross-field dimension, is very rapid on the western edge of the disturbance and is associated with a gradient in total electron content (TEC), which entails a decrease in column density of about 1×10^{17} electrons/m².

The generation of plasma bubbles in the nighttime equatorial ionosphere is by now, a much-studied and reasonably well-understood process. In some cases, the bubble growth is moderate or stalls at an early stage, leaving a large, westward tilted density depletion in the bottomside F-region [Tsunoda, 1981]. Although the large-scale growth stage of the bubble itself has ended, its edges can structure as a result of the gradient drift instability. At these local times, the zonal neutral wind is large (≥ 150 m/s) and eastward, so that westward-directed plasma gradients are unstable. Therefore, the westward edge of an upwelling is most likely to develop intermediate-scale structure. This behavior is consistent with Figure 4 which is a simple model based upon our Δ TEC and scintillation data for Leg 1. The vertical extent of the bubble can only be guessed. There is no question, however, that the west wall is structured in regions where the plasma drift vector and the density gradients are parallel.

In Figures 3(b) through 3(e), the intensity scintillation and Δ TEC for subsequent cuts through the drifting bubble are shown. For westward legs, the time scales have been reversed and expanded to match those eastward, in both direction and distance. The relative eastward/westward time scales were ascertained by first locating, in space (Figure 1), the westward intensity scintillation or depletion boundaries for consecutive legs. This yields a cross-field, macroscale drift of ~ 90 m/s throughout the observation period at a penetration altitude of 350 km.

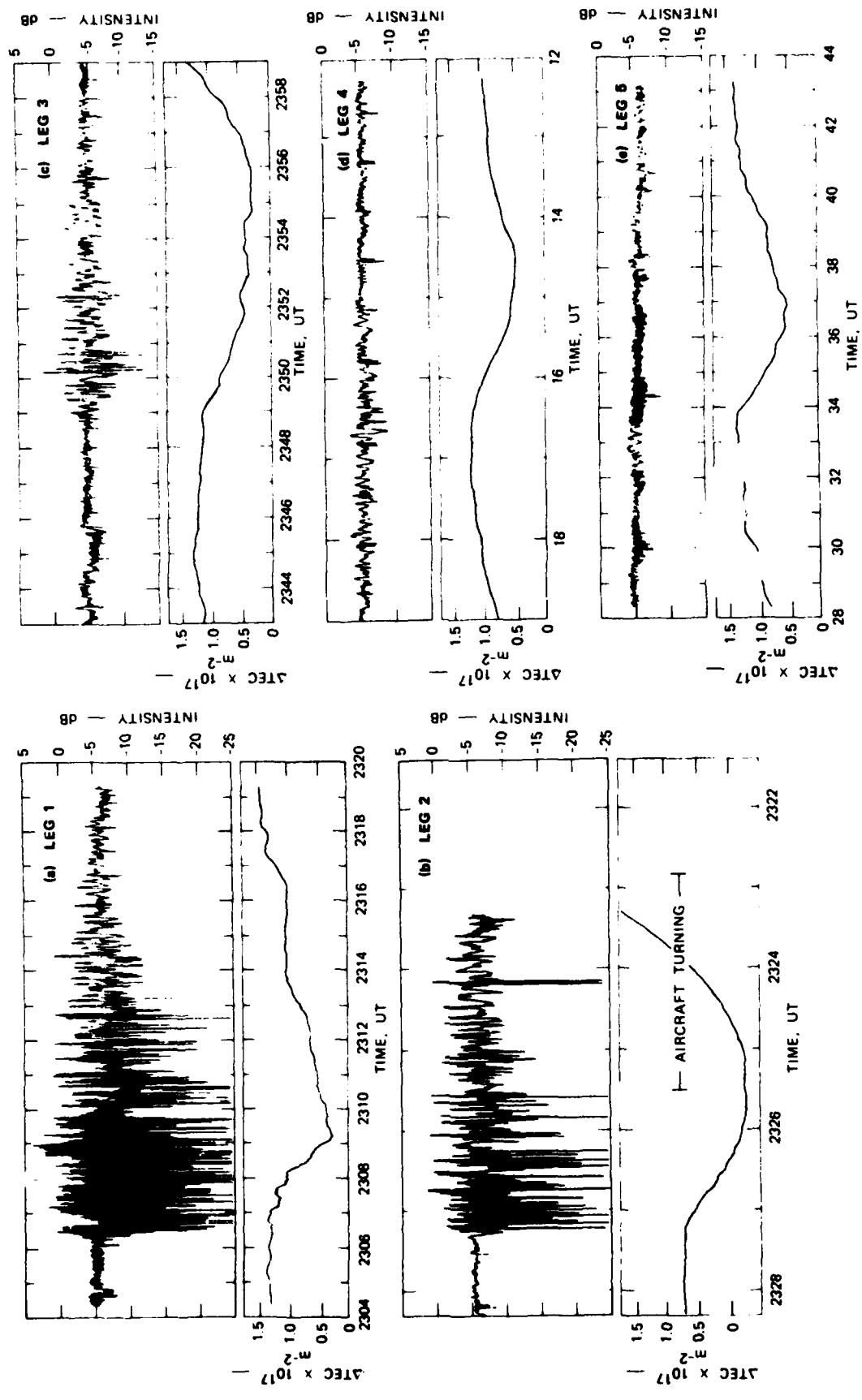


FIGURE 3 INTENSITY AND PHASE RECORDS FOR SCANS THROUGH THE BUBBLE

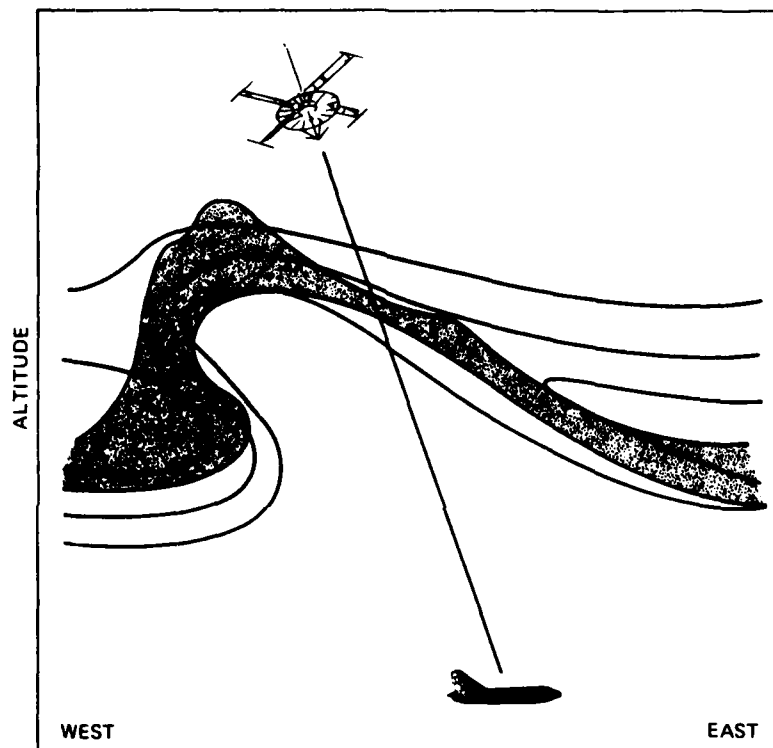


FIGURE 4 ONE POSSIBLE CONFIGURATION OF ELECTRON DENSITY (CONTOURS) AND IRREGULARITY DISTRIBUTION (SHADED) THAT DUPLICATES THE OBSERVED SIGNAL STRUCTURE

By comparing flight legs in Figure 3 it can be seen that the intensity scintillation declines rapidly to a level indistinguishable from the noise level by the fourth leg, but the Δ TEC pattern remains nearly constant in form. (On the second leg, the phase data is distorted before 2325 UT by rapid aircraft deviation from straight and level flight.)

IV PHASE SPECTRA AND IRREGULARITY DECAY

The intensity records in Figure 3 effectively illustrate the east-west asymmetry in, and temporal decay of > 400 -m spatial scale irregularities. The phase data and, in particular, the temporal changes in energy and the shape of the phase spectra from leg to leg, can be used to determine the decay rate quantitatively and provide information about possible decay mechanisms.

In Figure 5, the phase spectra of the overall bubble are shown for the three eastbound Legs (1, 3, and 5). These have been offset from one another by 10 dB for clarity. By including the entire bubble in each spectrum, we can observe structure in spatial wavelengths from the ~ 80 -km outer scale down through about 400 m. For the eastbound flight, the bubble drifts with the aircraft, producing an effective scan rate of ~ 110 m/s. This establishes the correspondence between the temporal and irregularity cross field spatial scales shown.

The spectrum for Leg 1 is in a familiar experimental form (although no theory has yet successfully predicted this power law index). It is nearly power law with an average spectral index near -2.5 ; this slope and the spectral density levels agree well with those observed in morphological studies of irregularity spectra at the equator [e.g., Livingston et al., 1981]. Such a phase spectral index corresponds to a one-dimensional rocket or satellite spectrum with index of -1.5 . We consider it, then, to be the signature of a region sampled during, or shortly after, Rayleigh-Taylor or gradient drift structuring or both, as already suggested. For Legs 3 and 5, however, sampled some 40 and 70 min after Leg 1, the spectra have considerably steepened through energy decay at short spatial scales. For purposes of discussion, we will use the break in the spectra, which this decay creates near 4 km, as the dividing line between two different regimes.

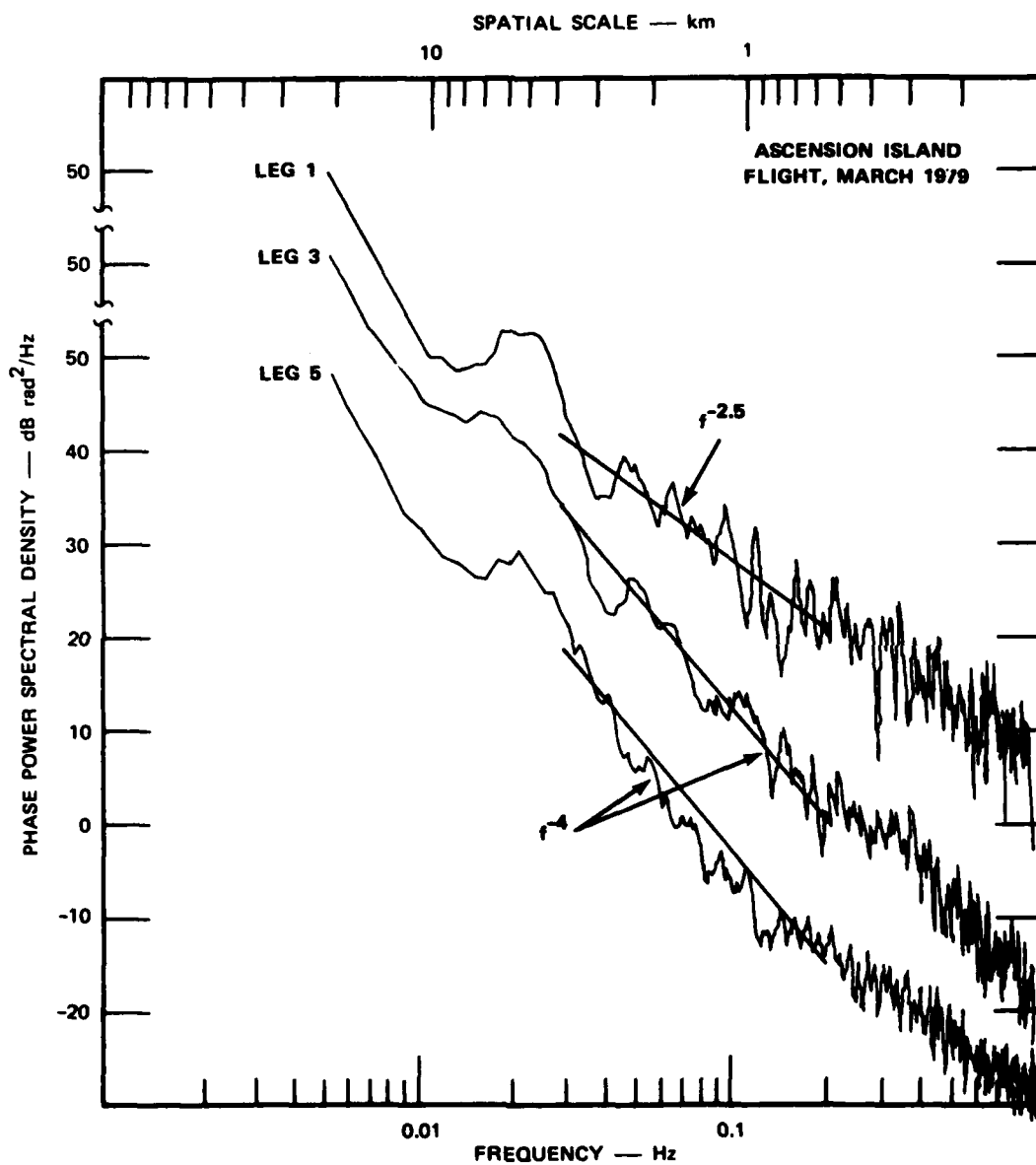


FIGURE 5 PHASE POWER SPECTRA FOR THE BUBBLE

At spatial scales larger than about 4 km, the spectra are nearly equal in shape and in energy content for all flight legs. The decay at the peak is only about 5 dB in 70 min. Because the scintillation technique is sensitive to $(\Delta N)^2$ rather than $(\Delta N/N)^2$, however, some of the decrease may be caused by lower absolute plasma density. A detailed interpretation of the spectral features in this large-scale regime, which is dominated by aeronomic processes [Booker, 1979], is beyond the scope of this paper. The broad enhancement in energy centered near 7 km, which is made conspicuous by the energy depletion near 15 km, may be a remnant of the larger-scale perturbation (e.g., a gravity wave), which initiated the bubble. We note that this feature is very similar to that seen in the in situ electron density spectra presented by Kelley et al. [1982a].

Of more interest to the present study, and in contrast to the stability of large scale structure, that, at short scales decays rapidly during the observation period. For example, at an irregularity scale size near 1 km, the energy decays at an even rate of ~ 9 dB per hour from Leg 1 to Leg 3 to Leg 5. Using the relationship

$$|\Delta N|^2(k, t_0 + \tau) = |\Delta N|^2(k, t_0) \exp - \{2k^2 D \tau\} \quad , \quad (1)$$

we find a diffusion coefficient for $k = (2\pi/1000 \text{ m})$ of $7 \text{ m}^2/\text{s}$. On the other hand, the classical ambipolar cross-field diffusion coefficient (which is equal to twice the electron perpendicular diffusion coefficient) is given by

$$D_{\perp c} = 2\rho_e^2 v_e \approx 0.96 \text{ m}^2/\text{s} \quad . \quad (2)$$

The diffusion coefficient at the 1-km scale is thus considerably greater than the classical ambipolar rate.

As we discuss more fully below, an enhanced diffusion rate is not difficult to explain. What is more interesting is the fact that a single diffusion coefficient (independent of k) cannot be used to describe the process. For example, by choosing $D = 7 \text{ m}^2/\text{s}$, we can match the decay

rate at 1 km, but that is the only scale at which the decay rate is matched by the classical formula given in Eq. (1). This result is illustrated in Figure 6 where Eq. (1) has been solved at a time, τ_0 , corresponding to Leg 5 with an input spectrum $|\Delta N|^2(k, t_0)$ matched to the Leg 1 data (the straight line in Figure 6 is the least squares fit to the data in Leg 1). The solution matches the observed spectrum at 1 km. However, the experimental decay rate is considerably higher at longer wavelengths and considerably slower at shorter scales.

The data in Figure 5 provide an opportunity to determine empirically the scale-size dependance of the diffusion rate, $D_\perp(k)$. Over the scale-size regime $400 \text{ m} < \lambda < 4 \text{ km}$, the spectra in Figure 5 are nearly power law with slopes of -2.5, -4, and -5, respectively. By equating the value of $|\Delta N|^2$ at 4 km for three such power law spectra and differencing the curves at all other scale sizes, we can solve Eq. (1) for $D_\perp(k)$. The result is plotted in Figure 7. The curve represents the average between differencing Leg 5 and Leg 1 and Leg 3 and Leg 1. The error bars indicate the differences in the two estimates. This empirical $D_\perp(k)$, of course, depends on the model in the sense that Eq. (3) assumes that each Fourier mode decays independently of the adjacent modes. As discussed below, it is unlikely that the physical mechanism or mechanisms that lead to the observed anomalous decay characteristics share the property of mode independence. The $D_\perp(k)$ that we have found should thus be regarded as both empirical and model dependent.

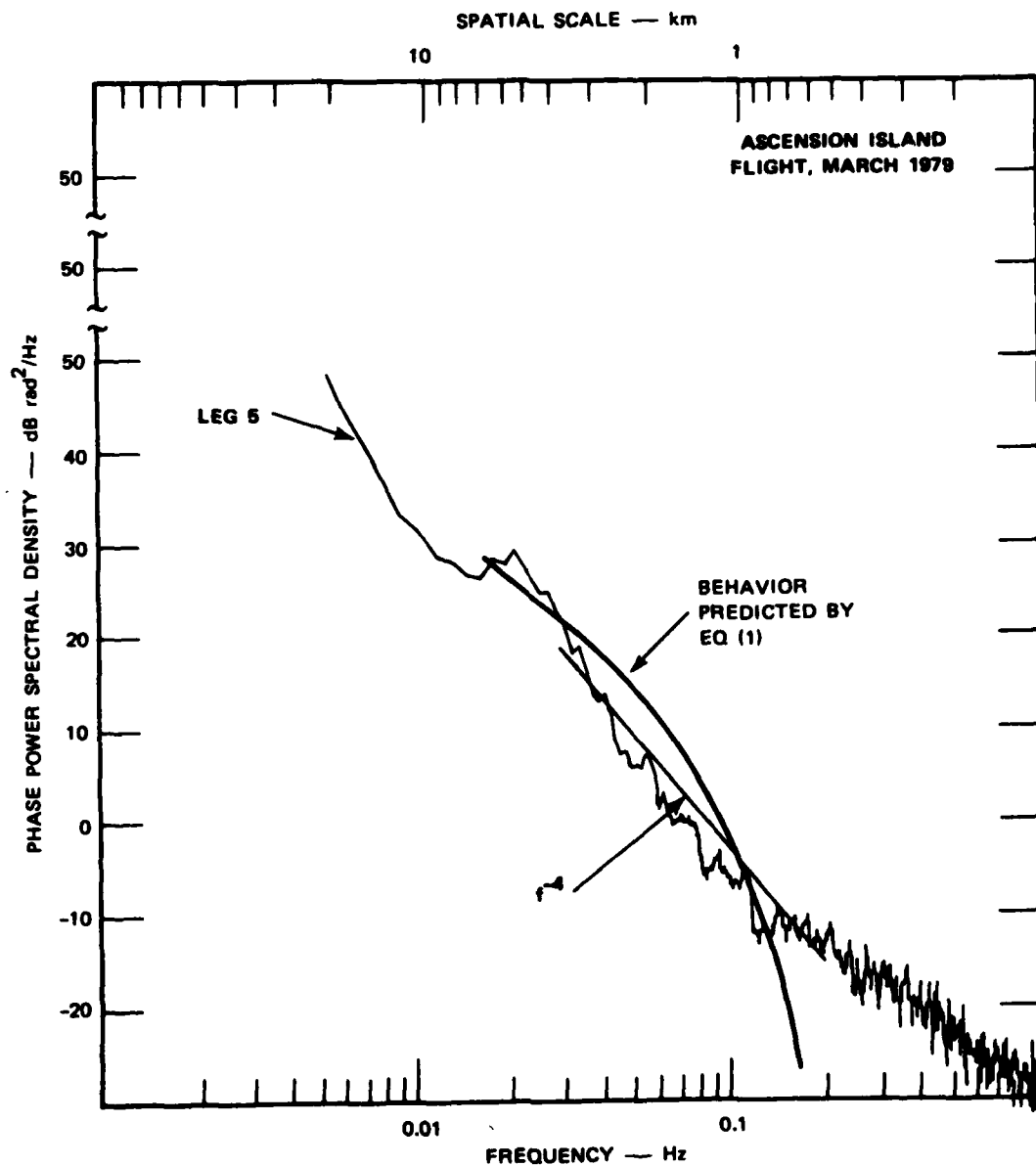


FIGURE 6 COMPARISON OF OBSERVATIONS OF THEORETICAL PREDICTIONS
BASED ON EQ. (1)

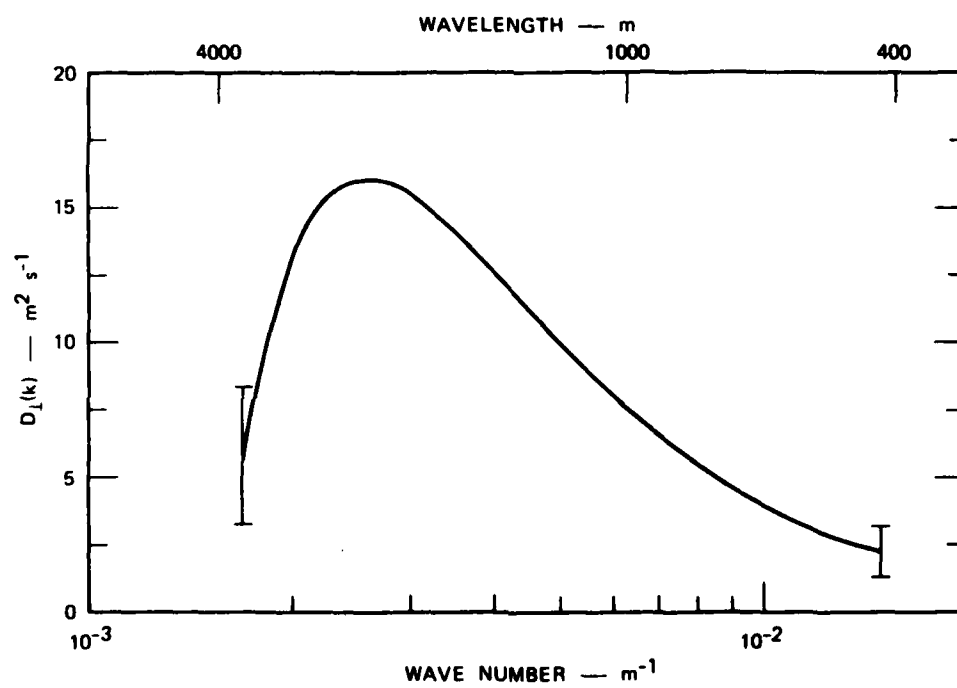


FIGURE 7 EMPIRICALLY DERIVED DIFFUSION COEFFICIENT

V DISCUSSION

A. Enhanced Classical Diffusion

A diffusion coefficient enhanced with respect to the ambipolar rate [Vickrey and Kelley, 1982] can be understood as follows. The ambipolar rate occurs when the more rapid perpendicular ion diffusion leads to a space-charge electric field that severely limits the ion flow and slightly enhances the electron velocity. An equilibrium results in which the two fluids diffuse at the same rate. Now if field-aligned currents can flow, for example, to a "conducting end plate" such as the E region in the auroral zone [Vickrey and Kelley, 1982], the ambipolar electric field can be "shorted out" and diffusion proceeds at the faster rate determined by

$$D_{\perp c} = \frac{\Sigma_1^F}{\Sigma_1^F + \Sigma_e^F + \Sigma_P^E} (D_{\perp e} - D_{\perp i}) + D_{\perp i} \quad (3)$$

where the Σ_P are the height-integrated Pedersen conductivities. The E region is of little importance in the nighttime equatorial zone. However, the conjugate F region has almost by definition a comparable height-integrated conductivity that, when substituted for Σ_P^E above, implies that $D_{\perp c} \approx 0.5 D_{\perp i}$. Taking $v_{in} = 0.6 \text{ sec}^{-1}$ and $\rho_1 = 5 \text{ m}$ corresponding to a height of 350 km yields $D_{\perp c} = 7 \text{ m}^2/\text{s}$. Thus, the enhanced diffusion rate is not as surprising as the observed wavelength dependence; i.e., the rate of diffusion could be explained classically, but the spectrum of decaying turbulence is another matter. In the next two sections, we investigate two mechanisms that produce diffusion whose rate depends on scale size.

B. The Drift-Wave Hypothesis

Costa and Kelley [1978a,b], Burke et al. [1979], Huba and Ossakow [1981], Kelley [1982], and perhaps others have suggested that drift waves play an important role in F-region diffusion. In linear theories these waves are destabilized by gradients in the plasma and, in their nonlinear state, act to smooth out the gradients, which produce them. The result is anomalous diffusion of the driving structure.

Gary [1980] has analytically studied anomalous diffusion due to drift waves. The waves grow at wavelengths such that $k_{\perp} \rho_i \gg 1$, which corresponds to wavelengths below about 40 m. Kelley et al. [1982b] and Kelley [1982] have compared the amplitude and spectral forms of both density and electric field fluctuations predicted by Gary [1980] and by Bernhardt et al. [1982] in this wavelength regime, and found excellent agreement with data obtained in the topside equatorial spread F environment (i.e., altitudes > 280 km).

Gary's analytical form for the anomalous diffusion coefficient is

$$D_a = \frac{\pi}{9} \left(\frac{KT}{M} \right)^{3/2} \left(\frac{1}{\Omega i} \right)^2 \left(\frac{1}{n} \frac{dn}{dx} \right) \quad (4)$$

which can also be written

$$D_a = 1.29 D_{\perp i} (Kl) \quad (5)$$

where l is the ion mean free path parallel to the magnetic field, (V_{in}/v_{in}) , and K is the gradient scale-length, $(1/n \, dn/dx)^{-1}$, wave number of the driving scale. For a sinusoidal driver with wavelength of 3 km, corresponding to the break in the spectrum and a mean free path of 450 m, $D_a = 1.2 D_{\perp i} \approx 17 \, \text{m}^2/\text{s}$.

This result is in reasonable agreement with the present data set in the sense that the enhanced decay at long wavelengths may be explained. Because the drift waves themselves only occur at very short wavelengths, however, one must hypothesize a link in k space for this mechanism to be

valid. In fluid turbulence theory, such a linkage occurs in the inertial subrange where energy is passed between adjacent wave numbers, leading to a cascade from large to small scales. The net effect is to maintain the energy level in the intermediate range, with dissipation occurring at short wavelengths.

These arguments must remain somewhat speculative because turbulence theory is not as well developed in plasma applications. The data are not inconsistent with these concepts, however, provided an analog of the inertial subrange exists in plasmas.

C. The Image Formation Process

An alternative mechanism that produces a scale size dependent loss of F-layer structure has been proposed by Vickrey et al. [1984], who have investigated the formation of image striations in the E layer theoretically. Images result from the finite compressibility of the E-region ion gas. Because the electron gas is incompressible in both the E and F regions, however, the image formation process redistributes electrons along the magnetic field line such that $\nabla \cdot J \equiv 0$.

The model calculations of Vickrey et al. [1984], show that the saturated E region image spectrum has a peak near 1 km and scale size in agreement with near-equatorial rocket observations. Because the image irregularities grow at the expense of F layer plasma, Vickrey et al. [1984], argued that the "effective" diffusion rate in the F layer would reflect, at least qualitatively, the scale-size dependence of the image formation process. The present observations support that argument. It should be kept in mind, however, that the observed spectrum is a balance between possibly scale-size dependent drivers and loss mechanisms. Nevertheless, the present observations support a "nondriven" situation in which the spectral evolution is determined purely by diffusion processes. A quantitative time-dependent cross-field diffusion model including magnetic field-line coupling effects is currently being developed and will be reported elsewhere.

VI SUMMARY

We have shown unique airborne observations of the spectral evolution of ionospheric structure in an isolated, decaying plasma bubble. The temporal behavior of the decaying plume structure suggests that the loss mechanism of structure is scale-size dependent. The effective cross-field diffusion rate deduced from the observations is scale-size dependent and in qualitative agreement with the theoretical model described by Vickrey et al. [1984].

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